

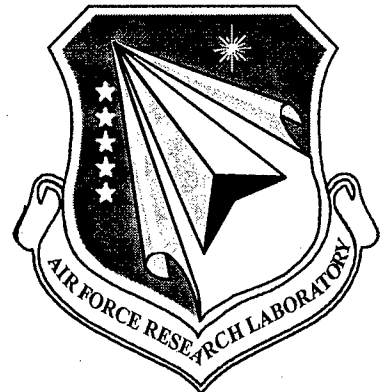
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FEASIBILITY OF NON-INTRUSIVE AND REMOTE IDENTIFICATION OF
CHEMICAL CONTAMINANTS USING GROUND PENETRATING RADAR (GPR)

Dr. Aka G. Finci
Mission Research Corporation (MRC)
1720 Randolph Road, SE
Albuquerque, NM 87106-4245

Mr. Daniel F. Stanfill III
Detection Sciences Inc. (DSI)
496 Heald Road
Carlisle, MA 01741

Program Manager: Mr. Thomas Brantley
AFRL/MNMI
101 West Eglin Blvd
Eglin AFB, FL 32542-6810



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AARON D. BRINSON
Technical Director
Ordnance Division



THOMAS D. BRANTLEY
Program Manager

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Table of Contents:

<u>Section</u>	<u>Page</u>
NOTICE	i
LICENSE RIGHTS LEGEND	i
REPORT DOCUMENTATION PAGE (FORM 298)	ii
1 INTRODUCTION	1
2 PROGRAM OVERVIEW	1
2.1 BACKGROUND	1
2.2 SCOPE	2
2.3 PROGRAM OBJECTIVES	3
3 TECHNICAL APPROACH	3
3.1 COMPARISON OF EXISTING TECHNOLOGIES/METHODS	3
3.1.1 LIST OF APPLICABLE EXPLOSIVES/CHEMICALS	3
3.1.2 SENSOR REVIEW	4
3.1.3 FIELD TEST DEMONSTRATION	7
3.2 TECHNICAL MERITS OF GPR and ELECTROMAGNETIC RADIOGRAPHY (EMR)	10
3.3 SUPPORTING SAMPLE TEST/SURVEY DATA	13
4 CONCLUSIONS	27
5 RECOMMENDATIONS	28
<i>Distribution List</i>	30

List of Figures:

<u>Figure</u>		<u>Page</u>
1	EMR Site Map Showing Distribution of TCE.....	16
2	Natural Infiltration Zones, Sultanate of Oman.....	17
3	Vertical Migration of TCE in Infiltration Zone, Princeton, IL	18
4	Vertical Migration of TCE in Infiltration Zone, Shreveport, LA	20
5	Radar Survey Map of Gasoline Station.....	21
6	Signature of Contamination Plume with 5.3 ppm Benzene	23
7	Dynamite Burial Pit/Wyoming.....	24
8	Nitroglycerine Map/Taiwan.....	25
9	Nitroglycerine Map/Canada.....	26

List of Tables:

<u>Table</u>	<u>Page</u>
1 Applicable Explosives/Chemicals with Their Concentration Levels	4

1. INTRODUCTION:

This "Final Report" has been prepared for the **Air Force Research Laboratory, Munitions Directorate, AFRL/MNMI, Eglin Air Force Base (AFB)**, Florida, by the **Mission Research Corporation (MRC)** and its subcontractor, **Detection Sciences Inc., (DSI)**, under the SBIR Phase I contract F08630-97-C-0071.

The format and the contents of the report are in accordance with the requirements outlined in the "Armament Directorate Technical Report Guide," issued by the Department of the Air Force, Wright Laboratory, Eglin AFB, Florida. The Government Project Manager was **Mr. Thomas Brantley**, (850) 882-2203, extension 2248. The contract Principal Investigator (PI) was **Dr. Aka G. Finci** of MRC, (505) 768-7600, extension 739. The main technical point-of-contact (POC) from DSI was **Mr. Daniel F. Stanfill III**, (978) 369-7999.

2. PROGRAM OVERVIEW:

2.1 BACKGROUND:

The possibility of remotely detecting buried/underground materials and objects has fascinated mankind over centuries. A technique that could potentially render the ground and its contents clearly visible is so attractive that considerable scientific and engineering efforts have gone into devising suitable methods of exploration.

One of the major areas of concern is the variety of materials contained in conventional munitions which could be hazardous to the environment. Among them we can count various explosives, electronic components, plating materials, heavy metal alloys, and a number of associated hazardous chemicals.

Military installations have designated test and firing ranges for munitions testing and training purposes. During and after these activities, some of the chemical and explosive residues remain in or on the soil, while the rest may be deposited onto the surface where vegetation lies or is dispersed into the atmosphere.

Precise identification and mapping of the contaminated areas are very desirable from environmental and safety points of view. However, the conventional techniques carry with them four major drawbacks: they are costly, they are time consuming, they are intrusive, and they do not provide 100 % coverage.

A remote, non-intrusive detection technique would be ideal to detect the chemical contaminants in the soil. The technique would make use of the specific properties of the contaminants and identify the affected/contaminated areas/volumes in a timely manner.

Ground probing or surface penetrating radar has been found to be an exceptionally attractive option. The technique has a particular appeal to practicing scientists and engineers in that it embraces a wide range of specialized fields, such as the electromagnetic (EM) wave/radar signal propagation in lossy media, ultra wideband and directional antenna technology, integrated

system design, extremely short pulse feature, discriminant waveform signal processing, image processing, and computer software development.

The ground penetrating radar (GPR) concept has been in use for about twenty years, in contrast to fifty years or more for the conventional radar systems. The original incentive for its conception was military in nature: the need to detect tunnels and land mines. Later the utilities, such as the water and gas pipe lines and power lines represented a form of keen interest from the industry. Fairly recently, the GPR has become of great interest to geophysicists and hydrologists because of their unprecedented potentials. It would take a devoted paper here simply to summarize its non-military applications. There have indeed been a large number of applications in the past; yet there will be greater needs in the future.

GPR is a particular realization of the ultra-wideband, extremely short pulse radar technology. Impulse radar creates an exciting challenge to the innovative research and development arena. The related technology is largely application oriented, drawing its most important feature from the inherent fact that the method is **non-intrusive** and **non-destructive**. Although on a smaller scale than the conventional military applications, this technology can become a successful commercial value in itself, and could be proven to be a worthy and beneficial venture for its forefathers.

2.2 SCOPE:

The overall technical scope of this Phase I effort was to assess/develop technologies to remotely detect and identify environmentally damaging residue resulting from conventional munitions development and testing.

To achieve this, the scope of the Phase I program focused on the following efforts:

- ☒ To explore and evaluate existing remote detection and identification technologies for their potential use in detecting environmental contaminants.
- ☒ To evaluate chemical and other environmental contaminants to determine their specific properties that could be used in the detection processes of the developed technologie(s).
- ☒ To recommend candidate technologie(s) for non-intrusive and remote sensing applications after the above-mentioned evaluations.

Results of the assessment and evaluation efforts as mentioned above, and performed to meet the specific program objectives as outlined below, are presented in this "Final Report."

2.3 PROGRAM OBJECTIVES:

Phase I research provided assessment of the feasibility of deploying a non-intrusive and remote detection/sensing system for locating and identifying environmentally hazardous chemicals/residues resulting from munitions development and testing activities. Our main technical objectives are presented below:

- ☒ Produce a list of chemicals/materials used in conventional munitions to be made.
- ☒ US Air Force (Eglin Air Force Base) to be visited and the Munitions Directorate authorities at these locations to be consulted to make this list as complete and realistic as possible.
- ☒ EPA regulations to be studied and applied to this list to determine the "hazardous" status of the chemicals/residues in the list.
- ☒ Preliminary guidelines to be set forth as to what (parameters) to look for and what to record to locate the chemicals under consideration. The needed detection sensitivity, i.e., parts per thousand, parts per million (ppm), parts per billion (ppb) also to be determined.
- ☒ Existing non-intrusive, remote detection/sensing methods and technologies to be studied.
- ☒ Recommendation(s) to be made as to what method/technology is the most suitable and capable to satisfy the required sensing/mapping of the chemicals in question.

Phase II development and demonstration would ultimately be necessary for a full performance evaluation of the candidate technique.

3. TECHNICAL APPROACH:

3.1 COMPARISON OF EXISTING TECHNOLOGIES/METHODS:

3.1.1 LIST OF APPLICABLE EXPLOSIVES/CHEMICALS:

Our initial efforts were concentrated on a search for possible sources to obtain data on the electrical dielectric constants (ϵ), electrical conductivities (σ), and required detectable concentration levels of the explosive materials and chemicals. Following is a list of the sources we contacted:

- ◆ EPA/Region V/Chicago/Mr. Mark Vendl
- ◆ EPA/Region VI/Dallas/Mr. Warren Arthur
- ◆ Corp. of Engineers/CRREL/New Hampshire/Dr. Tom Jenkins
- ◆ American Environmental Network/Albuquerque/Dr. Mitchell Rubenstein
- ◆ University of New Mexico (UNM) Library/Albuquerque

- ◆ Methods Information Comm. Exchange (MICE)/Washington D.C.
- ◆ Detection Sciences Inc. (DSI)/Massachusetts/Mr. Daniel F. Stanfill III

With the help of the above sources and the suggestions received from the USAF, we compiled the data shown in **Table 1**.

Table 1. Applicable Explosives/Chemicals with Their Concentration Levels.

<u>EXPLOSIVE/CHEMICAL</u>	<u>CONCENTRATION LEVEL (µg/l)</u>
1,3-dinitrobenzene	50
2,4-dinitrotoluiene	0.2
2,6-dinitrotoluene	0.2
4-amino-2, 6-dinitrotoluene	---
2-amino-4, 6-dinitrotoluene	---
HMX	1800
Nitrate	10,000
Nitrite	1000
Nitrogen, ammonia	---
Nitrogen, total	---
Nitroglycerine (NG)	---
Nitroguanidine	700
2-nitrotoluene	61
3,4-nitrotoluene	61
PETN	---
RDX	10
Sulfate	250,000
Sulfide	---
1, 3, 5-trinitrobenzene	60
2, 4, 6-TNT	10
Tetryl	370

3.1.2 SENSOR REVIEW:

We have performed a broad scale review of various sensors capable of detecting/identifying chemicals in the ground. In general, we have tended to disregard "laboratory" type instruments that require insertion of a physical sample for analysis, such as mass spectrometers, gas chromatographs, or other "direct contact" instruments. Instead, we have focussed on non-contact, remote sensing instruments. The candidate sensors become even more limited if the sensors must detect chemicals that are buried in the ground, and not just chemicals that are on the surface of the ground.

To be able to "see" below the surface of the ground implies that the ground must be relatively transparent to the sensor. This requirement immediately eliminates visible sensors (multispectral sensors) and infrared sensors, because neither visible radiation nor infrared radiation can penetrate common earth materials, and can only "see" what lies at the surface of the ground. The only viable candidates for sensors that can "see" into the ground are sensors that utilize sound waves (seismic waves) and sensors that utilize electromagnetic (EM) radiation. They are presented below:

➤ **Shallow Seismic Surveys:**

If the ground is "soaked" with relatively high concentrations of liquid, the velocity and refractive properties of sound waves are affected by the presence of the liquid. A shallow seismic survey can detect these localized changes in velocity and refraction, provided that the changes are sufficiently strong to show up as an "anomaly," or contrast, compared to the prevailing, "background" velocities found in the general area. This type of approach can be useful in difficult situations, for example where the liquids are trapped beneath the concrete slab of a building and are not accessible by other means. It is possible to use a "bank shot," wherein the sound waves travel beneath the building and emerge out the other side where they can be detected by an array of geophones. A typical array consists of 12 geophones spaced 25 or 30 feet apart. Various sound sources, or energy sources, may be used, depending on the total depth to be explored and the degree of energy loss that the soil materials may have at that location. The energy source may be as small as a 5 or 8 pound hammer used to strike a steel plate on the ground. A more energetic source would be an 8-gauge shot gun shell (blank) that is fired from a gun (called a "Betsy") that is held to the ground. Still more energetic sources involve explosives such as a quarter stick or a half stick of dynamite. Typically, the source is fired at one end of a "string" of geophones and the process is repeated by firing the source again at the other end of the string. The total length of the string, including the spacing that separates the source from the nearest geophone, is usually around 400 feet. In the field, productivity is a matter of firing several strings in one day, totaling 2,800 to 4,000 lineal feet of coverage a day.

The principal drawback to shallow seismic surveys, irrespective of the relatively low productivity, is that natural variations in lithology and the corresponding variations in velocities tend to mask, or hide, all but the strongest variations that may be produced by liquids in the ground. In other words, the technique is not very sensitive, is relatively cumbersome to use, and requires relatively high concentrations of liquid to be detectable in the presence of natural variations in the background conditions.

➤ **Terrain Conductivity:**

There are two types of terrain conductivity (EM) instruments. One type is a time domain (TD) instrument that makes measurements as a function of time, thereby providing depth information. The other type of EM instrument makes "static" (non-time domain) measurements of electrical conductivity. These instruments are reasonably sensitive, but suffer from the same vulnerability to lithological changes as do the shallow seismic instruments. In general, the presence of ionic chemicals in the ground tends to increase the electrical conductivity of the earth, whereas the presence of non-ionic chemicals in the ground typically decreases the electrical conductivity. On

an absolute scale, these instruments are capable of detecting a change in conductivity of about 0.01 percent, or 1 part per 10,000, but natural stratigraphic changes or lithological changes can swamp out any electrical changes caused by low-level concentrations of chemical in the ground. The spatial resolution of these instruments is relatively poor, particularly in regard to the spatial resolution of GPR. Lithological changes, particularly point-to-point changes in ground moisture conditions, will produce localized variations up to about ± 6 percent. Even under dry, arid conditions where ground moisture is scarce and therefore relatively uniform, variability of about 1 percent can be expected for changes produced by inhomogeneities in soil moisture and soil composition. In other words, a chemical in the soil must produce localized changes in conductivity of at least 1 percent to be reliably detected, and more typically in the range of a few percent to be detected under average soil moisture conditions. In the end, there is no way to know whether a small electrical difference (anomaly) is caused by chemicals in the ground or natural lithological conditions as well as point-to-point variability of soil moisture.

➤ **Ground Penetrating Radar (GPR):**

The first ground penetrating radar systems (circa 1970) were used for locating pipes, profiling geologic strata and other subsurface tasks involving echo location, the sine qua non of radar technology. But GPR can be much more than an echo location device, as Detection Sciences Inc. has so amply demonstrated over the years. Starting in 1979, on what DSI believes to be the first site that GPR was ever used to investigate hazardous waste (the Picillo property "Pig Farm," Coventry, Rhode Island), DSI observed chemicals in the ground. This work, which was sponsored by the U.S. EPA Research Division in Cincinnati and by the MITRE Corporation, was first published in 1985^{1, 2}, pre-dating by nearly a decade any subsequent publications reporting on the observation of chemicals with GPR.

Since that first discovery, DSI has gone on to classify chemicals as being ionic or non-ionic, later refining their observations to include dense, non-aqueous phase liquids (DNAPLs) and light, non-aqueous phase liquids (LNAPLs). We can distinguish between liquid-phase contaminants trapped in the pore spaces of the soil, and dissolved-phase liquids in the ground water. **The chemical detection capability of DSI's present GPR system is concentration levels as low as a few parts-per-million (ppm) to upper parts-per-billion (ppb).** DSI has also shown that specific chemicals produce unique and different radar responses, and have authored a pre-publication release describing this work.

¹ Stanfill, D.F. III and McMillan, K.S., "Inspection of Hazardous Waste Sites Using Ground-Penetrating Radar (GPR)," *Proc. National Conference on Hazardous Waste and Environmental Emergencies*, p. 244-249, Hazardous Materials Control Research Institute (H.M.C.R.I.), Cincinnati, OH, May 1985.

² Stanfill, D.F. III and McMillan, K.S., "Radar-Mapping of Gasoline and Other Hydrocarbons in the Ground," *Proc. 6th National Conference on Management of Uncontrolled Hazardous Waste Sites*, p. 269-274, Hazardous Materials Control Research Institute (H.M.C.R.I.), Washington, D.C., November 1985.

GPR is essentially "immune" from having the chemical anomalies corrupted by the lithology. Quite simply, chemicals appear to be chemicals, and lithology appears to be lithology, but neither looks like the other. In other words, lithology can be seen for what it is, and chemicals can be seen for what they are, thanks to the high-resolution capability of our radar and the way(s) in which the radar responds to chemicals in the ground.

Therefore, we conclude from our study of technologies/methods for the non-intrusive location and mapping of explosives/chemicals that GPR is the candidate method for the required task.

➤ **Detection of Explosives with GPR:**

DSI has been working under contract with ICI Explosives USA and ICI Explosives Americas Engineering in Canada to use GPR to locate explosives in the ground at various manufacturing facilities that ICI owns in the U.S. and Canada. In addition to environmental considerations, concern has been focused on the safety aspects of remediating *nitroglycerine (NG)* because of a freak accident experienced by ICI. Nitroglycerine was known to be present in the ground, so ICI decided to eliminate the NG by detonation. Unfortunately, the NG was located in a geological fault and had traveled along the fault. When the NG was detonated, the explosion traveled a quarter of a mile along the fault and detonated a small building and killed two people in the building. This event led to ICI contacting DSI to determine if we could use remote sensing techniques -- particularly ground penetrating radar -- **to locate NG in the ground.**

NG is denser than water and is relatively insoluble in water, making it a generic dense, non-aqueous phase liquid (DNAPL). DSI was totally confident of the ability of GPR to locate what amounts to a garden-variety DNAPL, but wanted to go to the next step and see if NG might possibly have any unique radar attributes that would allow it to be specifically identified as NG. To date, the field measurements have shown that NG behaves just as would be expected for any DNAPL in the ground, but as yet, no unique attributes have been observed that would allow NG to be singled out to the exclusion of other types of DNAPLs. This is not to say that unique, radar-observable properties do not exist, just that they have not become evident in the process of forming radar images of the NG in the ground.

3.1.3 FIELD TEST DEMONSTRATION:

A theoretical analysis of detecting chemical contaminants in the ground led to the conclusion that the current GPR system should have a detection threshold of about 50 parts per million (ppm). This is based on a criterion that DSI has created called, "noise equivalent dielectric" (with a nod to the infrared world, where "noise equivalent temperature" (NET), and "noise equivalent power" (NEP) are commonly used criteria for evaluating the performance of infrared systems). The noise equivalent dielectric is defined as the smallest change in dielectric constant that can be detected with a signal-to-noise ratio of 5 to 1. For our current radar system, this calculates to be a concentration level of about **50 parts per million**. We know, however, that we can reliably detect concentrations of **1.3 ppm** with ample signal-to-noise ratio, the inference being that the detection threshold is much less than 1.3 ppm and therefore must be in the parts per billion (ppb) range. One possible explanation is that we are looking at a large volume of material. Even though the concentration level is low, there can be a significant amount of contaminant contained

in several cubic yards of earth. For example, the "footprint" of the 120 MHz radar antenna is nearly 3 by 5 feet, or about 1 1/2 square yards at the surface of the ground. The radar beam spreads about ± 45 degrees (90 degrees total angle) in the fore and aft direction and about ± 20 degrees (40 degrees total angle) in the side to side direction. By the time the beam has penetrated to a depth of 10 or 20 feet or so, it is looking at many cubic yards of material. The total amount of contaminant contained in that volume of earth can be substantial, even at very low concentrations. A small volume of material buried in a shallow excavation may look more like a small, buried object rather than exhibiting the diffuse reflection properties we have come to associate with low level contamination dispersed in the ground.

Preparation of the Experiment:

As part of this program, MRC and DSI offered to conduct a "field test" at Eglin AFB to demonstrate the capabilities of the GPR as a non-intrusive method for the location/detection of explosives in the ground. Even though we were not given the chance to do so, we proposed the following protocols:

1. **Excavation.** Using a backhoe, dig a series of holes in the ground, at least 3 feet deep, preferably about 4 feet deep. The width of the excavation can be no wider than the backhoe bucket, and the length can be as short as the "wrist action" of the bucket that will allow the sand to be pulled out of the excavation. Each excavation should be spaced several feet from the neighboring excavation to isolate each excavation so that no "cross-contamination" can occur between excavations.
2. **Mixing.** Using a portable concrete mixer put a measured amount of the excavated sand in the concrete mixer; for example, 20 buckets (pails) of sand. To this sand, add one bucket of a "foreign substance," the description of which follows below. This would result in a 5 percent concentration of foreign material. Alternately, 30 buckets of sand could be used with 1 bucket of foreign material and the resultant mix would have a concentration of 3.3 percent. What is important is that the same percentage of foreign material should be added to the excavated sand so that the "concentration" of foreign material is the same for all excavations and that the concentration of foreign material -- regardless of what that foreign material may be -- does not vary from place to place.
3. **Moisture.** It may be necessary to add about a half bucket of water, possibly more, to the sand mixture to moisten the dry foreign material and bring the total mixture up to a moisture level that simulates natural soil moisture conditions. At Eglin AFB, we would expect normal soil moisture conditions to be upwards of 20 percent. The sand mixture should not become wet or visibly soupy, but merely simulate the feel and texture of the natural sand before the dry, foreign material is added to the sand.
4. **Filling.** The mixture of sand and foreign material should be placed at the bottom of the excavation to a uniform depth of at least 1-foot, preferably more, and covered with the remaining (unmixed) sand removed from the excavation. Because we are dealing with sand, compaction is not believed to be critical, though we would applaud vibratory compaction if this was available.

5. **Foreign Material.** The foreign materials to be mixed with the sand should first of all be environmentally harmless, and should be selected according to the following criteria:
- a. **Ionic Compounds.** We believe that ammonium nitrate is ionic, and is unusual in the respect that most explosives are organic compounds, and therefore most explosives should appear to the radar as non-ionic compounds. Ammonium nitrate (a common fertilizer) and table salt are both environmentally harmless, and therefore would make good candidates for ionic type of foreign materials to provide a contrast with other, non-ionic materials.
 - b. **Non-Ionic Compounds.** Table sugar is an environmentally harmless organic compound, and is expected to be observed by our radar as a non-ionic compound. Although sugar is an organic compound, it is not a nitrogen-based compound as would be the case for explosives. Garden fertilizer, particularly high-nitrogen fertilizer, would satisfy the nitrogen requirement, but synthetic chemical fertilizers are likely to be ionic, whereas organic fertilizer, while it may be non-ionic, is likely to be relatively low in nitrogen. Regardless of the anticipated electrical properties of any nitrogen-based compound, the radar should distinguish whether it is ionic or non-ionic.
 - c. **Explosives.** It is difficult to conceive of an explosive (other than black powder) that would lend itself to being safely mixed with sand in dilute concentrations. If the explosive is buried in concentrated form, it will appear to the radar as a buried "object," and therefore it will be rather hard to observe its chemical properties representative of a low-level contaminant in the soil.
6. **Weathering and Time.** We would expect that the buried materials, being environmentally harmless, could be safely left in the ground. It would be instructive to observe how the buried materials may behave over time, particularly when exposed to repeated episodes of rainfall. We would expect the ionic materials to become more dilute with time (because an ionic radar response implies solubility in water) and migrate vertically down into the ground. We would expect the non-ionic materials to more or less stay put, with some lateral migration in response to the hydrology of the site. The non-ionic materials may also become somewhat more dilute with time.

Test Setup and Conduct:

To arrive at a fair and representative test of the ability of the radar to respond to different chemicals in the ground, with particular interest focussed on nitrogen-based compounds, we proposed adherence to the following test conditions:

- ♦ There should be sufficient quantity of test material to make a layer at least 1 foot thick, extending over an area of several square feet, so as to appear to be something more than just a single, "buried object."

- ◆ The concentration levels are not critical, but should be the same for all of the material mixtures selected for study.
- ◆ There should be sufficient separation between adjacent excavations to prevent possible "cross-contamination" of substances due to lateral movement of rainwater in the ground.
- ◆ The type of material contained in each excavation should not be made known until after the testing is concluded and the results of the radar testing are made known to the Air Force. The reporting would consist of the radar properties observed at each excavation, including ionic versus non-ionic, and any other radar-observables that may distinguish one excavation from another, as well as those that may distinguish each excavation from the radar-observable properties of the surrounding soil (background conditions).

However, as mentioned earlier, we did not get the chance to perform this "field test" demonstration.

3.2 TECHNICAL MERITS OF GPR and ELECTROMAGNETIC RADIOGRAPHY (EMR):

As a result of U.S. weapons testing in the late 1960's and the subsequent research done on the propagation of electromagnetic pulses (EMP) at Kirtland AFB, NM, it was found that the ground is more transparent to electromagnetic pulses than had been previously thought.

In particular, in the frequency range of 10 MHz to 1 GHz, relatively modest amounts of power (less than a kilowatt of peak pulse power) can penetrate tens of feet into the ground. To the first order, the depth of penetration is governed by the square root of the peak pulse power and by the inverse square root of frequency. More importantly, the strongest influence on the depth of penetration is the attenuation [A (dB/meter)] of the electromagnetic impulse, which is a direct function of the electrical conductivity [σ (mhos/meter)] of the ground:

$$A = 12.86 \times 10^{-2} f \sqrt{\epsilon_r} (\sqrt{\tan^2 \delta + 1} - 1)^{1/2}$$

$$\tan \delta = \frac{\sigma}{2\pi f \epsilon_0 \epsilon_r}$$

where:

f = frequency

ϵ_r = relative dielectric constant

ϵ_0 = dielectric constant of free space (8.85×10^{-2} Farads/meter)

δ = angle of loss tangent (dissipation factor).

Because the depth of penetration is governed by the resistivity (inverse conductivity), for purposes of ground-penetrating radar it has been customary to focus on the resistivity of the ground, rather than the electrical conductivity. By employing low-noise electronics in the receiver with optimal filtering of the noise bandwidth, as well as trading off signal integration

time, it is possible to achieve about 8 feet of penetration per ohm-meter of resistivity in a production environment. This scale is not linear with resistivity, but is useful as a rule-of-thumb for estimating the depth of penetration in relatively adverse conditions where resistivities run in the single range. For example, most clays have resistivities in the upper single digit range, and penetration depths in the range of 50 feet can be achieved at an operating frequency of 120 MHz. A production environment is where the antenna is moved over the surface of the ground at a pace of about 3 miles per hour. Even if the speed is slowed to an average speed of 1 mile per hour, ground coverage would be more than 40,000 lineal feet in an 8-hour day. The 120 MHz antenna covers a swath that is nearly 5 feet wide, becoming progressively wider as the beam penetrates the ground. Some 200,000 square feet of surface area, extending to a depth of about 50 feet, can be inspected in a single day. In terms of volume, this amounts to the inspection of some 350,000 cubic yards of earth per day.

In general, it is desirable to use as high a frequency as possible, consistent with the depth of penetration that needs to be achieved. This will result in the best spatial resolution for the task at hand. Although spatial resolution is important for imaging discrete objects, such as buried drums, temporal resolution in the time domain can be more important. Noise can cause time-domain "jitter," which can effect the apparent temporal resolution. For this reason, low-noise electronics is important not only for improving the depth of penetration, but also for providing a more clear look at the physical properties of the reflecting surface. In particular, the coefficient of reflection (ρ) is given by the relationship:

$$\rho = \frac{\sqrt{\epsilon_1} - \sqrt{\epsilon_2}}{\sqrt{\epsilon_1} + \sqrt{\epsilon_2}}$$

As can be seen by the equation, the dielectric constant of the medium above the reflecting surface (ϵ_1) relative to the dielectric constant of the medium below the reflecting surface (ϵ_2) is all-important in determining the strength of the reflection coming from this interface. This is a critical consideration in the ability to detect low-level chemical contamination in the ground. The presence of the chemical contaminant effectively changes the dielectric constant of the host material, which produces a reflection at the boundary of contaminated and uncontaminated soil. **This is the fundamental reason why GPR/EMR can detect chemical contamination in the soil.** We can go the next step and define how small a change in the dielectric constant can be detected. This is very much a function of the internal noise of the receiver, which sets a "floor" on how small a signal can be detected. Conservatively, by assuming a ratio of peak signal to RMS noise of 5:1, the smallest change in the dielectric constant that can be detected with our present equipment is less than $\Delta\epsilon = 10^{-5}$. Remembering that the signal beam covers a relatively broad area, and that the total amount of contaminant within the beam may be in the order of grams, rather than micrograms, the ability of the GPR/EMR system to detect contamination levels in the low parts-per-million (ppm) to upper parts-per-billion (ppb) range comes about not only as a result of high sensitivity, but also as a result of sampling more than a few cubic centimeters of material.

Having reasonable penetration with relatively high sensitivity is only the entry point for detecting chemical contamination in the ground. At this juncture, it is important to draw broad

distinctions between two specific types of chemicals. **Ionic chemicals**, which include acids, bases and salts, modify the electrical conductivity of the ground. Typically, this causes a localized increase in the electrical conductivity, resulting in higher attenuation. The attenuation produces a lighter-than-normal contrast relative to baseline conditions. This is the method by which ionic chemicals can be detected in the ground. The degree of attenuation; i.e., the degree of contrast, is governed by the concentration of the ionic chemical.

Conversely, **non-ionic chemicals**, which include organic chemicals, solvents, pesticides, and petroleum products, as well as most explosives such as nitroglycerine, modify the dielectric constant of the host material. Granted that ionic chemicals also modify the dielectric constant; but the dominant mechanism of ionic chemicals is to modify the electrical conductivity, whereas the non-ionic chemicals modify the electrical conductivity to some degree, but the dominant mechanism is the dielectric constant. Another way to look at the problem is to consider the electrical conductivity and the dielectric constant as vectors 90 degrees apart, with ionic chemicals arrayed more along one axis and non-ionic chemicals along the other axis. In all cases, the reflection coefficient is complex, but empirical experience with the two types of chemicals in the field makes it relatively easy to classify chemicals as ionic or non-ionic.

Ionic chemicals tend to be soluble in water, whereas non-ionic chemicals tend not to be. The lack of solubility of non-ionic chemicals gives rise to a term frequently used in the hazardous waste community — *a non-aqueous phase liquid*. In practical terms, this generally means that the solubility in water is only a few tenths of 1 percent, or less. The lack of solubility is important in the way that the liquid behaves in the ground, but so is the density, or specific gravity, of the liquid in determining the migration characteristics of the liquid. This gives rise to the general classifications of dense, non-aqueous phase liquids (**DNAPLs**) versus light, non-aqueous phase liquids (**LNAPLs**). Examples of LNAPLs are gasoline or fuel oil, which tend to float on top of the water table. DNAPLs, on the other hand, are denser than water and migrate vertically down through the water table until they encounter some sort of confining or semi-confining layer such as clay or bedrock. Examples of DNAPLs are most of the common solvents, such as trichloroethylene (TCE) or benzene. By virtue of the fact that these liquids do not readily dissolve in water, the edges of the contaminated zone are very sharply defined, whereas the edges of ionic chemical contamination tend to be much more diffuse. A sharply defined vertical migration column ("sinker") is almost certain to be a DNAPL, irrespective of whether it is seen to penetrate the water table or not. If it is seen to penetrate the water table, then the evidence is conclusive that the liquid is more dense than water, as well as being a non-aqueous phase liquid, as evidenced by the sharply defined edges of the vertical migration column. Irrespective of the density issue, sharply defined edges, even in the soils above the water table (vedoes zone), provide conclusive evidence that the contaminant is a non-aqueous phase liquid (**NAPL**), and not an ionic, or relatively soluble liquid.

LNAPLs are seen to spread horizontally on top of the water table, and this characteristic can be used to identify the liquid as an LNAPL. If there is sufficient liquid present, it can be seen to form an "inverted bubble" in the water table, with a sharply defined boundary between the floating liquid and the underlying water.

These physical characteristics are "structural" in nature, and are within the imaging capability of high-performance ground-penetrating radar (GPR). Beyond these physical characteristics, however, lie some intriguing characteristics that we have designated as **electromagnetic radiography (EMR)** to set it apart from GPR. Whereas conventional radar is fundamentally concerned with echo-location, or the "structural" aspects of the target (RADAR = RAdio Detection And Ranging), EMR is concerned with the physical attributes of the reflected signal, including frequency domain, phase, polarization and complex signals emanating from the way that various chemicals, or groups of chemicals, respond to being irradiated with brief impulses of electromagnetic, radio-frequency (RF) energy. At present, the physics of this behavior area is only poorly understood, but is certain to be a result of quantum effects and discrete energy transitions. The bulk of the evidence is empirical, by observing that certain chemicals behave in certain ways, and produce certain characteristic signatures. Experience on hundreds of hazardous waste sites involving thousands of man-hours of observation have shown us that these signatures are repeatable, predictable, and are remarkably independent of the host material in which the chemical is contained. We call attention to the two chemical signatures of nitroglycerine (**Figure 8** and **Figure 9** in the next section) taken a half world apart, respectively, in Taiwan and in Canada, and the remarkable similarity of the DNAPL signature and the way that it has vertically stratified into two distinct zones.

At the present time, it is not possible to use EMR as a stand-alone technology to uniquely identify these signatures as being nitroglycerine (laboratory testing of soil samples was used to verify the EMR results); but these signatures were sufficiently unique, particularly in comparison to other signatures on these sites, that a strong circumstantial case could be made that these signatures were produced by nitroglycerine and not any of the other chemicals known to be used in plant operations or directly in the manufacturing process. In other words, there was no reason to believe that any of the other chemicals commonly used in conjunction with the manufacture of nitroglycerine would produce these particular signatures.

Given that other types of geophysical instruments produce single-variable information (such as measuring the electrical conductivity), the relative "richness" of the multi-variable information generated by the GPR/EMR technology, particularly those as yet unexploited variables such as measuring discrete energy bands (frequency bands), underscores the technical merits of the EMR/GPR technology.

3.3 SUPPORTING SAMPLE TEST/SURVEY DATA:

Having developed and field-tested the underlying technologies on hundreds of hazardous waste sites over the past 18 years, there is no doubt that EMR can fulfill several required US Air Force missions. Validation of our capabilities would greatly facilitate the acceptance of EMR technology. There is a need for non-invasive, comprehensive, low-cost site assessment on a worldwide basis, not only for known hazardous waste sites, but to comply with the legal requirements for site assessments. EMR can also be used for monitoring the progress of clean-up activities, and for locating power lines, air vents, and apertures connecting underground bunkers and structures to the outside world.

During a typical survey, we establish a survey grid with reference to permanent physical features, and run parallel survey lines spaced 5 feet apart in the selected survey area. We survey to a nominal depth of 48 feet. All data is stored (magnetic media). The "hard copy" graphic charts (vertical profiles) are then examined for anomalies, and the location of these anomalies, along with a description of each anomaly, are shown on a computer-generated (CAD) map of the site. A separate table, listing grid coordinates and depths of all anomalies, is supplied. It is anticipated anomalies may consist of such items as chemicals in the ground classified as ionic versus non-ionic; DNAPL versus LNAPL; and liquid phase trapped in the upper soil (vedoes zone) versus dissolved phase in the groundwater. We map the horizontal and vertical extent of any underground structure/bunker, and chemical plumes, including vertical migration columns of DNAPLs.

One of the most important discoveries to come out of our work with EMR is the ability to locate infiltration zones. When rainwater infiltrates the ground, it does not do so in a uniform manner. There are preferential locations, or infiltration zones, where surface water more easily percolates into the ground. These locations are often topological lows. They are characterized by a loss of fine grain material (fines) and are less dense and more permeable than the surrounding soil. The loss of fines implies the existence of an underlying aquifer that acts as a horizontal "conveyor belt" to carry away the fines. Otherwise, the fines would have no place to go, and would "pile up" and decrease, rather than increase, the soil's permeability.

When DNAPLs are held above a confining layer, they are laterally transported in response to the hydrology of the site. When the DNAPL encounters an infiltration zone, the zone acts as a natural "sump," or collection point, to vertically transport the DNAPL down to the underlying aquifer. The EMR technology is uniquely suited to finding these locations, which are the controlling features. Other anomalies, if observed, may include faults, fracture zones, infiltration zones, and any geological features that may be important to the characterization of the site, including sand and clay lenses, bedding planes (trends), topological lows, subsurface ridges, peat deposits, etc.

In the following paragraphs we present some of our previous real survey data that are relevant to this US Air Force program:

Newark AFB. There have been many "landmark" surveys where we achieved some sort of landmark result or technical breakthrough. One such survey was performed for the US Air Force at Newark AFB, Ohio (O'Brien & Gere Engineers, AF contractor). We detected low level contamination beneath a reinforced concrete floor inside a steel building at the base. (To the best of our knowledge, no other contractor can accomplish this). Using our custom designed, high performance EMR system, we located a vertical migration column of CFC 113 (Freon 113) beneath the reinforced concrete floor of a clean room in Building 5. Slant drilling (by O'Brien & Gere) outside the wall of the building showed the concentration level of the column to be 31 ppm. At the other end of the room, dissolved phase CFC 113 could be seen layered in two distinct strata in the shallow water table beneath the concrete floor. Slant drilling showed the upper stratum to be 2.7 ppm CFC 113. The lower stratum was shown to be 1.3 ppm.

We have demonstrated different chemicals produce unique and different responses (spectral signatures) to electromagnetic radiation. In so doing, they show their presence in the soil and groundwater, even in very dilute concentrations. EMR can map a chemical and distinguish it from other neighboring ones. DSI performed a survey (*DSI, Final Report-GPR Survey, Princeton, Illinois*) and produced an EMR site map indicating the TCE distribution shown in **Figure 1**.

Sultanate of Oman. DSI teamed with the Remote Sensing Institute of Boston University working for the Ministry of Water Resources in the Sultanate of Oman searching for water in the desert. We were paying particular attention to naturally occurring infiltration zones because their location and presence implies the existence of an underlying aquifer. Infiltration zones have a more "grainy" appearance than the surrounding soils because of the loss of fine grain material. Because the fines must have gone somewhere (matter doesn't just disappear), there must be a means of transporting the fines away from the infiltration zone. An underlying aquifer acts as a horizontal "*conveyor belt*" to transport the fines away from the infiltration zone, leaving the local soil less dense and more permeable. **Figure 2** shows such infiltration zones in the desert of Oman. There was also a *graben* at this location, (*DSI, Final Report-GPR Survey, Sultanate of Oman*). The "tick marks" along the top of the chart are increments of 5 feet of travel. Finally, after many years of observing and reporting the locations of "sinkers" (vertical migration columns of DNAPLs), we made the important connection: *Sinkers tend to occur within infiltration zones*. And EMR is a unique tool for finding these features, which we believe, can be the controlling features on a site. We regard this discovery as a fundamental breakthrough in hazardous waste assessment.

DNAPLs move laterally in response to the hydrology of the site, until they encounter an infiltration zone. Then, they migrate down to the underlying aquifer! The infiltration zones are naturally occurring sinks, or sumps, where DNAPLs collect. More insidiously, they will continue to act as a source to feed the DNAPL into aquifer for many years to come, thus thwarting the "pump and treat" efforts in downstream wells.

Princeton, IL. **Figure 3** shows a vertical migration column of TCE at Princeton, Illinois, where we first realized the importance of infiltration zones on the migration characteristics of DNAPLs and nature of the connection pathways that these features provide by communicating with underlying aquifer. Smaller "patches" of TCE on the map (**Figure 1**) are also individual infiltration zones.

Shreveport, LA. Now that we appreciate the importance of infiltration zones, we can look back at earlier projects to gain a greater understanding of what we have seen. One such project was performed for a Fortune 500 company at a manufacturing facility in Shreveport, Louisiana, (*DSI, Final Report-GPR Survey, Shreveport, Louisiana*). This was also a TCE site. Nearly 10 years and millions of dollars were spent trying to clean up the site with "pump and treat" methods. Over the life of the project, only a few hundred gallons of product had been recovered. Our mission was to profile the confining layer and to look for a suspected ancient river channel. We found that the so-called confining "layer" did not exist, but instead consisted of a graded zone where the clays became progressively tighter (less permeable) over a vertical span of several feet. There were no significant, discrete "layers" in the clay. Under high

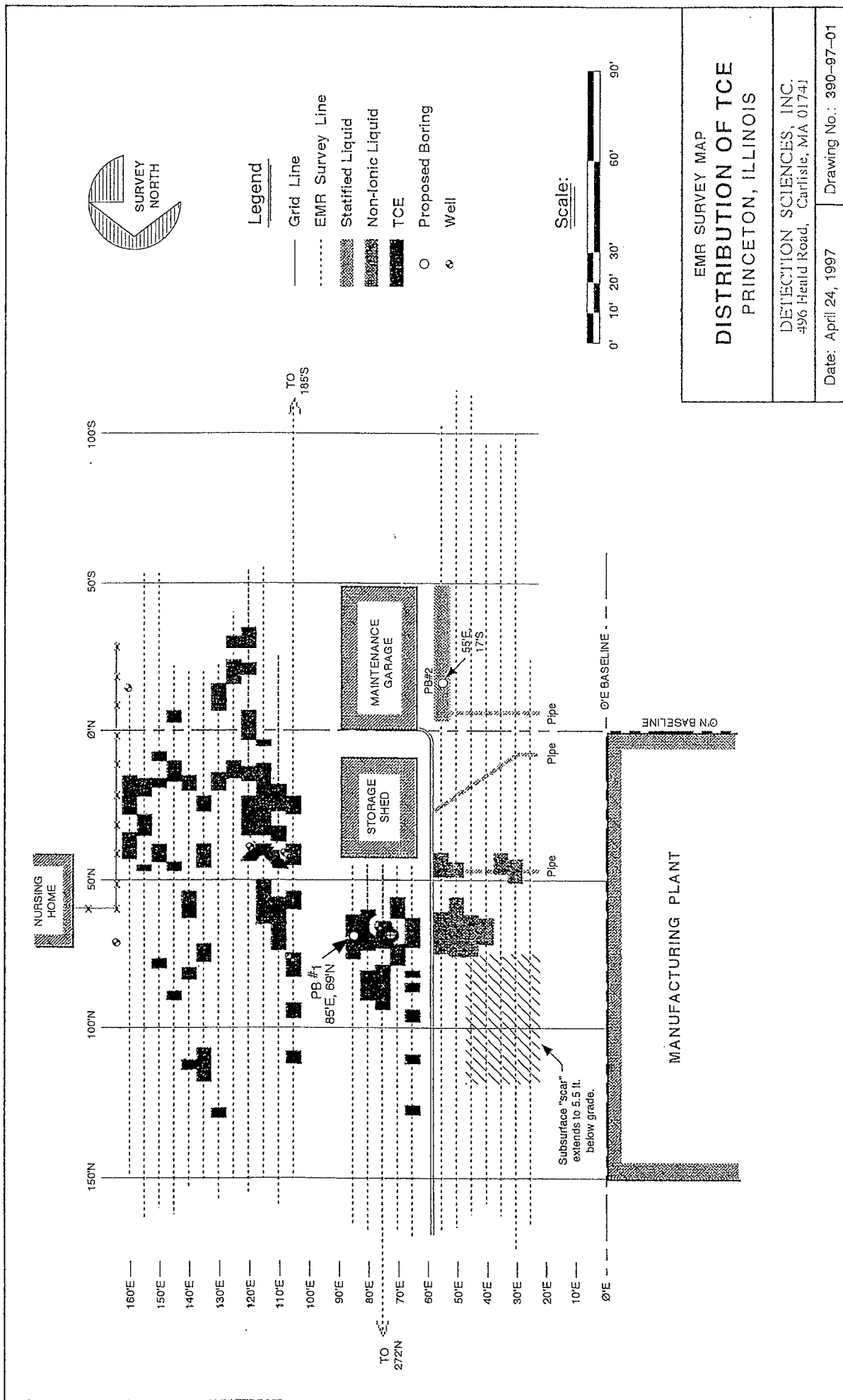


Figure 1. EMR Site Map Showing Distribution of TCE.

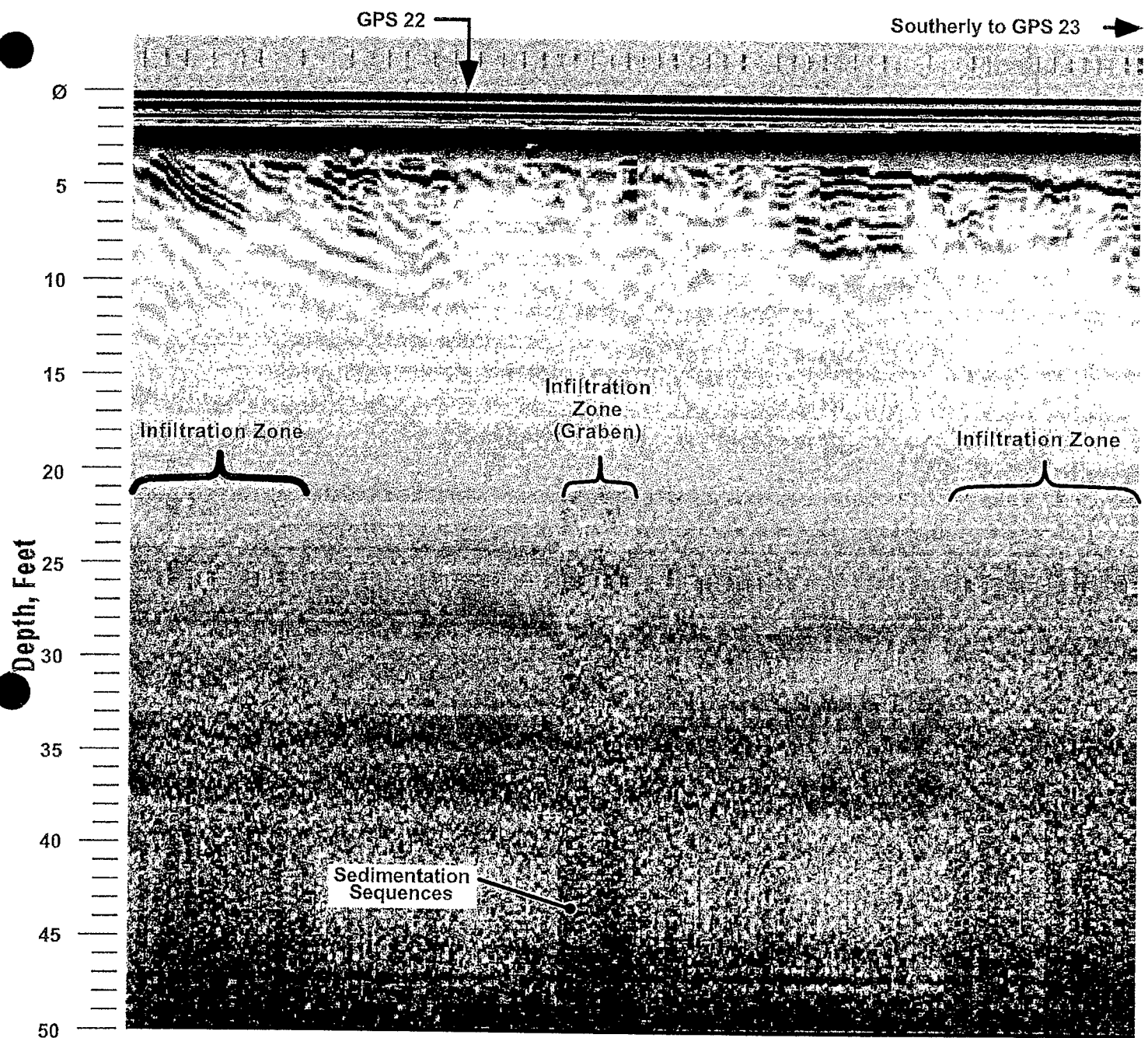


Figure 2. Natural Infiltration Zones, Sultanate of Oman.

VERTICAL PROFILE ALONG EMR SURVEY LINE 85'E

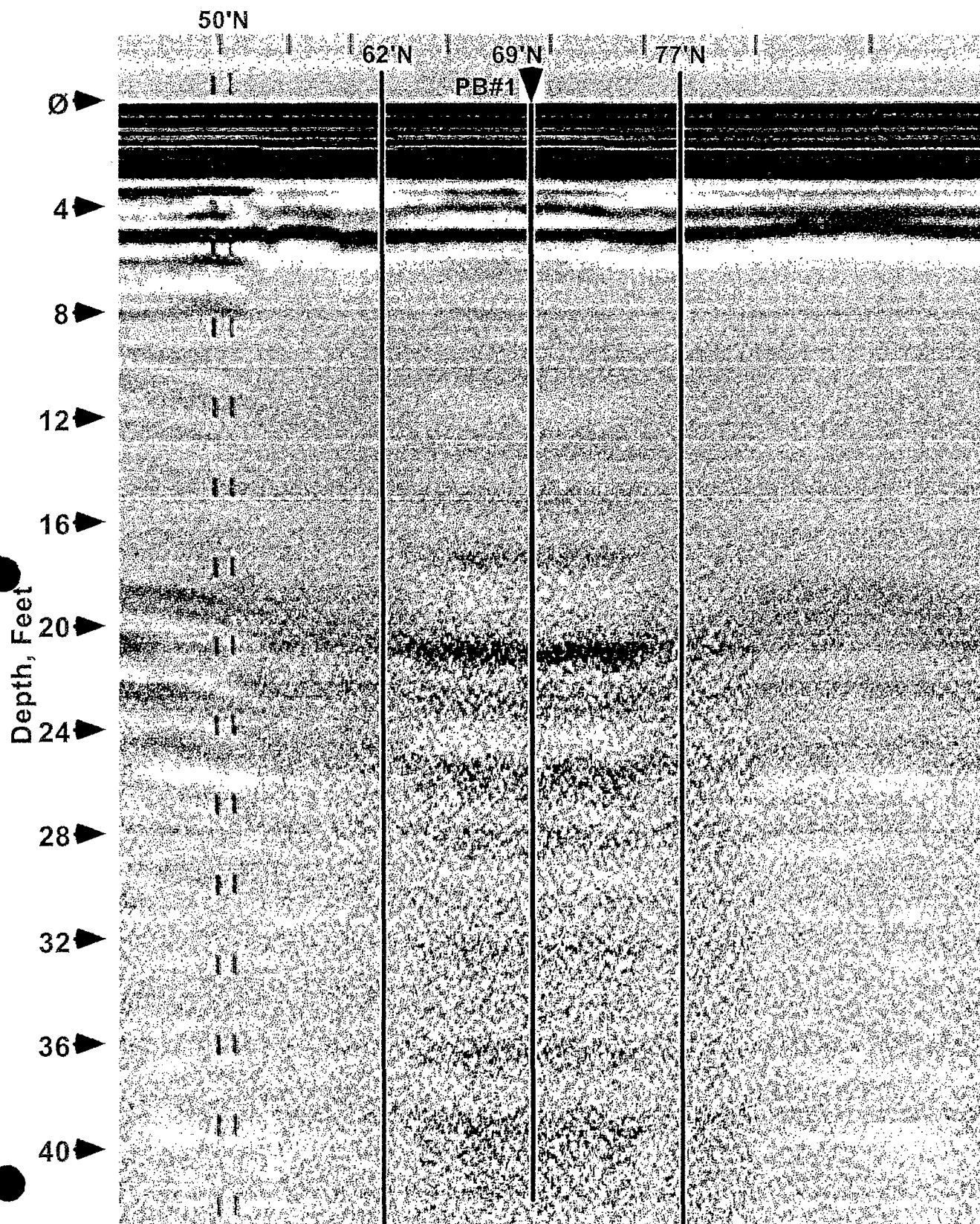


Figure 3. Vertical Migration of TCE in Infiltration Zone, Princeton, IL.

magnification, there were numerous, small bedding layers in the deposited clays (this is in the Mississippi Delta), but no single layer could be defined as the "confining layer." Moreover, the bedding deposits were horizontally discontinuous, and could not be "traced" for any significant distance across the site. The EMR showed variations in vertical permeability in the relatively uniform clays, allowing us to identify a zone where some degree of confinement or retardation was taking place, but there was no single, specific boundary to define the depth profile of the "confining layer" as such. We recommended to the owner to verify our claims by drilling.

Figure 4 shows two localized, vertical migration columns of TCE that we now know to be infiltration zones. We proposed placing a boring at this location, despite the fact that there was a recovery well less than 20 feet away. Upon drilling at this location, vapor levels were encountered that indicated concentration levels in the thousands of ppm. There is now a recovery well at that location. The yields in the new well are now running much higher than the old well. We attribute the difference to the horizontal tightness of the clay, where the permeability of the infiltration zone is much higher than that of the surrounding clay. There are subtle clues to be observed in Figure 4. The apparent lack of product (dark reflectors) in the upper clay indicates that the product spread laterally across the semi-confining zone until it ran down the infiltration zones. In other words, this was not a surface spill, or there would be more product trapped in the pore spaces of the upper clays above the infiltration zones. We can also see evidence of vertical retardation taking place within the vertical column, thereby producing the darker "banding" starting at a depth of about 24 feet down the migration columns. This banding provides direct evidence of the decrease in permeability (confinement) that is taking place at these depths. The important fact is we have identified pathways where the product was getting into the underlying aquifer. We did find the ancient (Pleistocene) river channel at a depth of about 38 feet. It appeared to be acting as a conduit to transport contamination off site. We proposed locating a boring to coincide with the extended alignment of the river channel and found there was significant dissolved phase TCE in the groundwater at the that location. Drilling also confirmed the existence of this ancient river channel.

Gasoline Station. **Figure 5** shows a radar survey map of a gasoline station. When the station first opened, some 4,000 gallons of gasoline leaked from the south pump-island. The clean-up contractor installed an interceptor trench, an air-stripping unit and pumped the water back into recharge. Our survey showed that channel flow had cleaned up the south pump-island, but that the site had other problems. There is very little free product, but there is a significant amount of liquid gasoline trapped in the pore spaces of the soil. The distribution of the affected soil is what is shown on the map (not free product). The tanks had been replaced, with clean fill placed between the tanks; but the surrounding soil still contained gasoline. Some of the gasoline has flowed northward, along a sewer pipe trench. The bulk of the gasoline had flowed more southerly, and had crept around the more permeable foundation of the convenience store. The isolated patch east of the pump islands was the location of the former pump-island before the present station was built. The isolated patch at the southwest corner of the property was a former storage area. The large patch in the southeast corner of the site shows the interceptor trench did not draw from this area. This figure illustrates the shortcomings of conventional methods compared to directly viewing what lies beneath the ground.

EMR SURVEY LINE 10'E

Proposed Boring 194'N

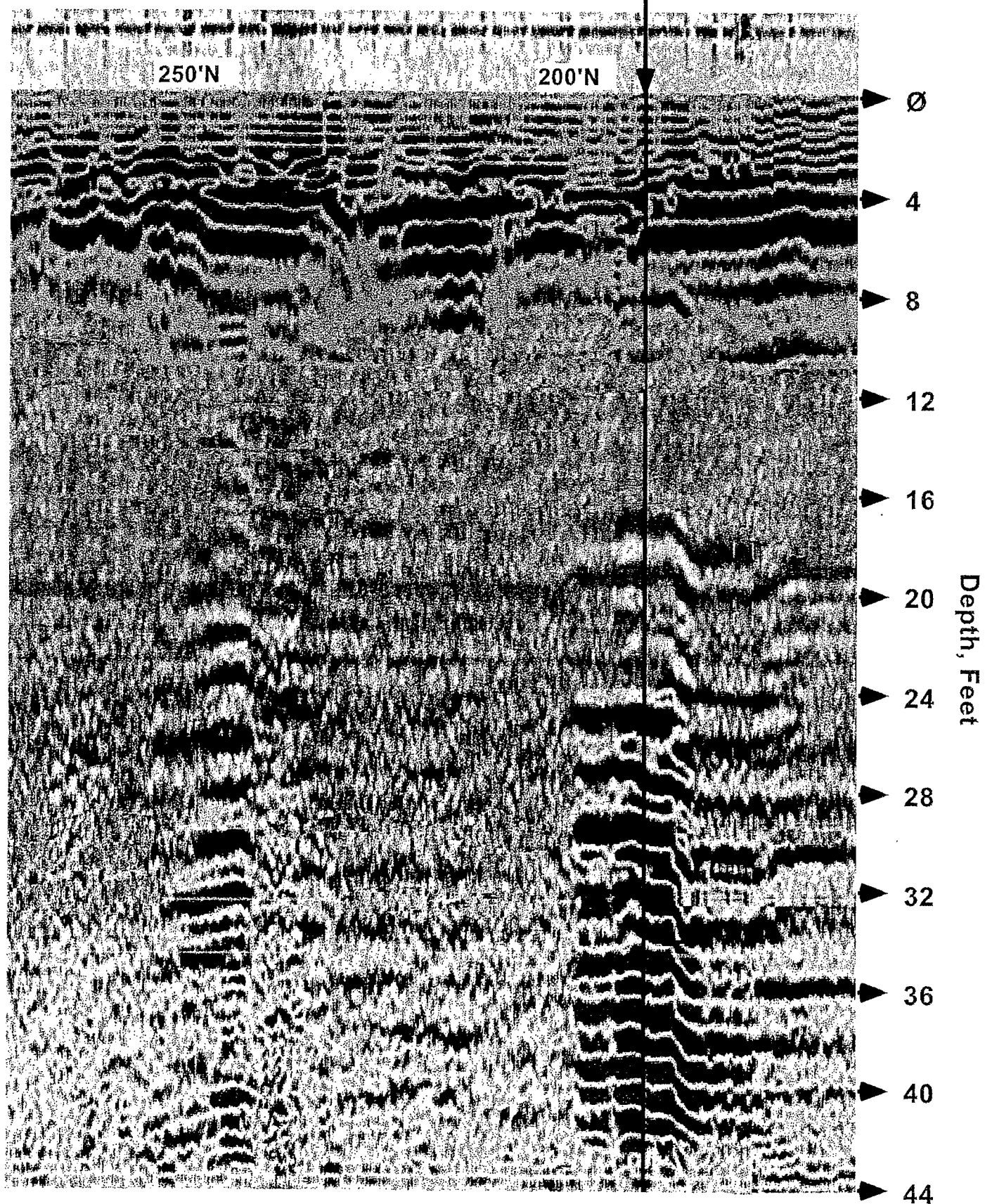


Figure 4. Vertical Migration of TCE in Infiltration Zone, Shreveport, LA.

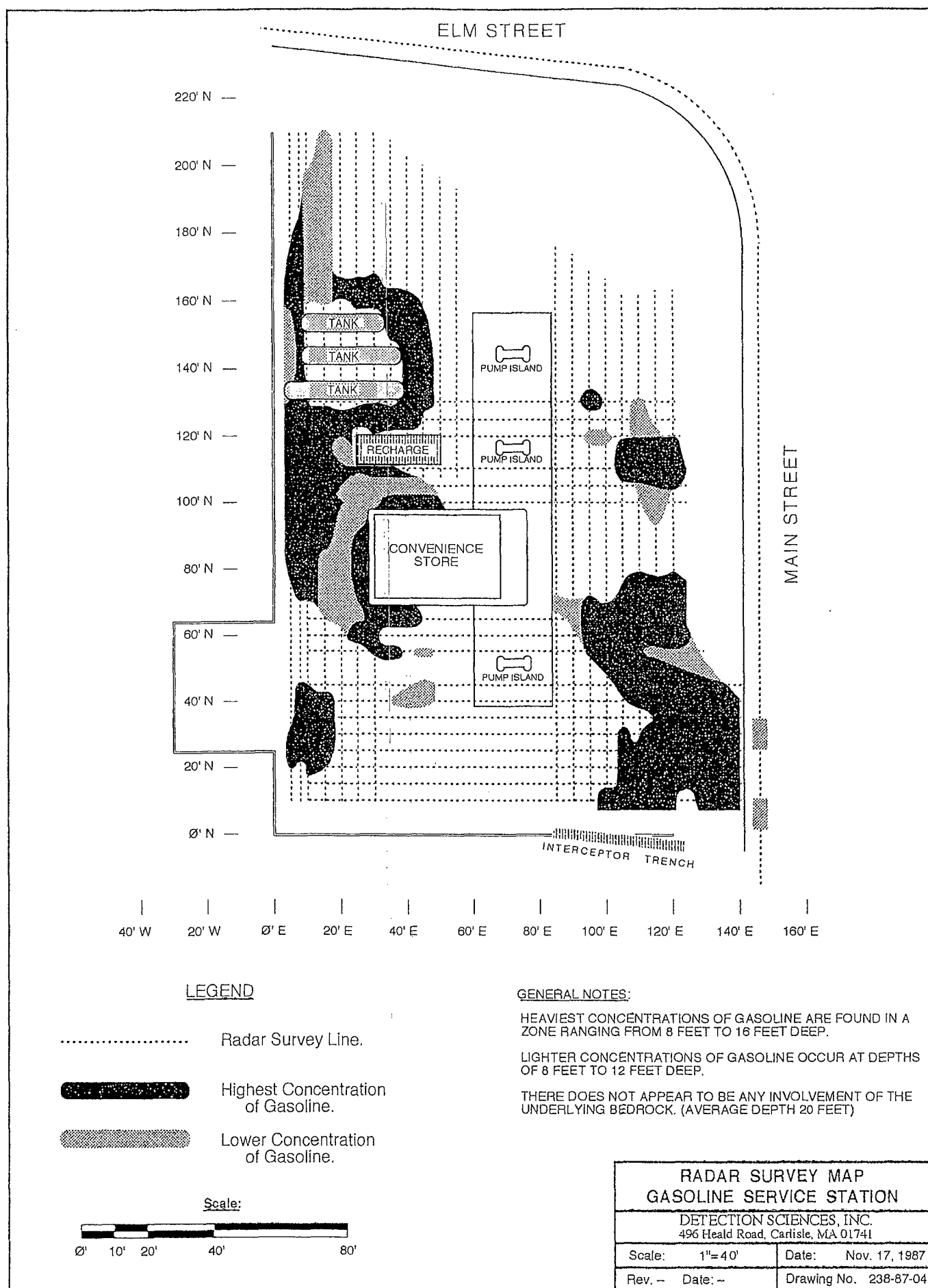


Figure 5. Radar Survey Map of Gasoline Station.

Norfolk, VA. Another example is illustrated in **Figure 6** showing the radar signature of a contamination plume. Tick marks on the horizontal top-axis correspond to 5-foot spacing. Following soil testing showed the plume to be 5.3-ppm benzene. There appears to be a fault passing through the plume that is allowing some of the benzene to migrate vertically downward, continuing below the bottom of the chart (24-foot depth). Some benzene appears to have collected to the right of the fault, starting at a depth of about 15 feet. This plume, which appears to have emanated from a neighboring refinery, was discovered in the course of a site inspection for the property transfer of a grain elevator in Norfolk, Virginia (*Final Report, J250-88, Tabor Engineering Service Inc., Norfolk, VA*). This survey was the first field test that made it possible to see low-level contamination in the ground.

Gillette, Wyoming. We searched for a burial pit in which dynamite was reportedly disposed (survey conducted for ICI Explosives, USA, Inc.). The client was anxious to determine the location of the burial, its lateral extent, its depth, and the amount of earth coverage that had been placed over the explosive. We found out that the anomaly reported by an EM survey team (Woodward Clyde) was merely produced by the disturbed earth from digging, but was not the actual burial location in question. Our radar successfully identified the size, the depth, and the location of the burial pit, as well as the amount of earth coverage over it. Furthermore, we also observed that a liquid substance, leachate, was migrating laterally out of one of the sides. **Figure 7** presents our radar profile. The vertical "white scars" migrating downward are the ionic signatures of the ammonium nitrate leaching into the ground. We also saw a non-ionic liquid signature leaching laterally out of the bottom of the pit, which we now know to be fuel oil that was mixed with the ammonium nitrate. The dynamite located by our radar was later destroyed by detonation.

Kaohsiung, Taiwan. **Figure 8** presents the resulting radar profile of a survey we very recently performed in Taiwan looking for explosive chemical nitroglycerine. The figure shows that the explosive was stratified in two distinct vertical zones, one around 17 feet of depth, and the other at around 31 feet.

Nobel, Canada. For our client ICI Americas, North York, Ontario, we located liquid nitroglycerine in the ground at a former manufacturing facility. The radar profile, **Figure 9**, shows the explosive extending down to a depth of 36 feet. Also note that the located nitroglycerine is again stratified in two distinct vertical zones, like what was observed in Taiwan, a half a world apart. An important point to make here is that the EMR signature of a particular chemical, in this case nitroglycerine, is independent of the host material, as illustrated by the comparison of the Taiwan and the Canada profiles.

We have *hundreds* of other case histories showing how EMR results are vastly superior to other conventional methods, and contribute much better understanding of the site conditions than any other method of site evaluation.

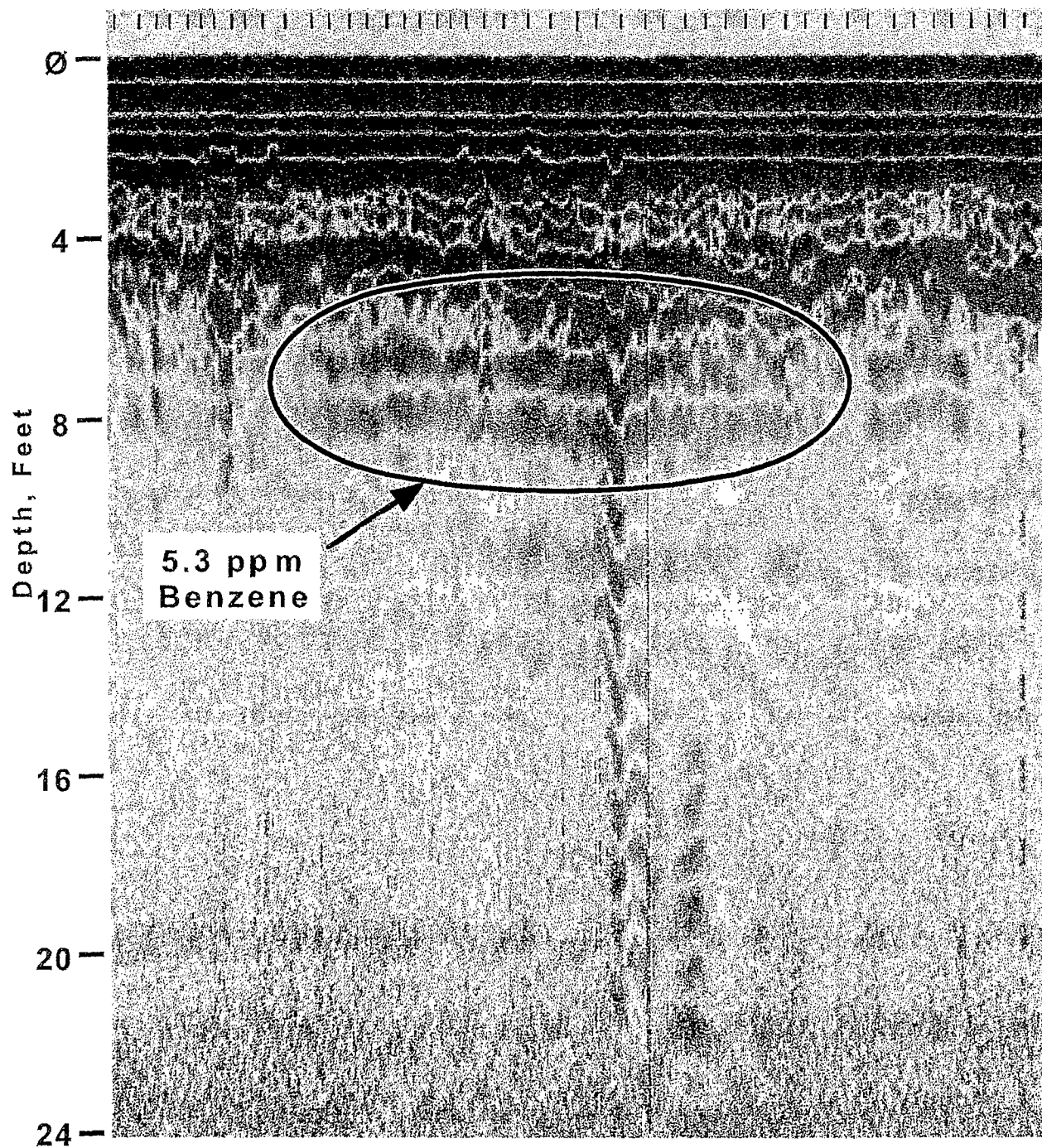


Figure 6. Signature of Contamination Plume with 5.3 ppm Benzene.

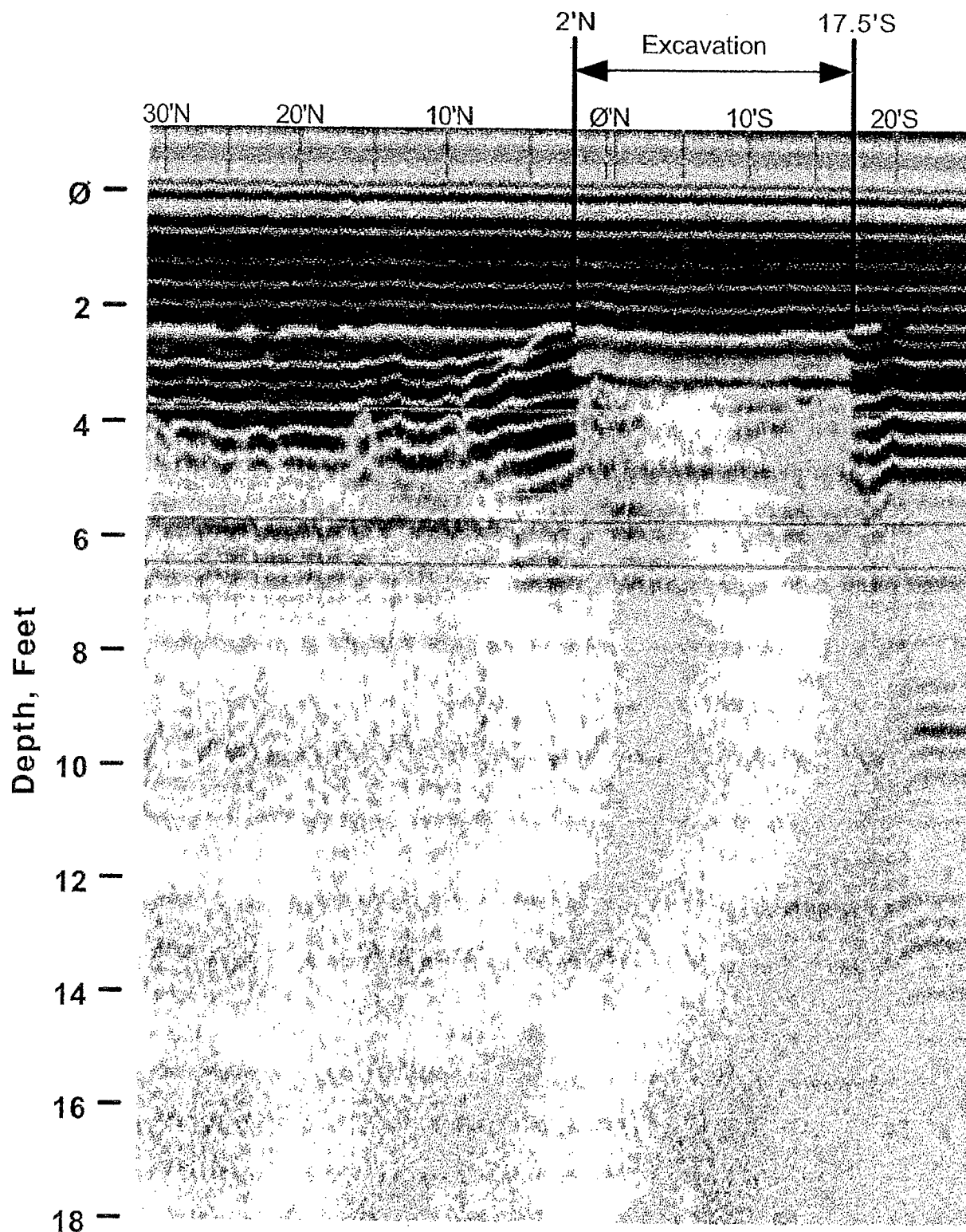


Figure 7. DYNAMITE BURIAL PIT/WYOMING:

EMR vertical profile of an excavation containing dynamite and ammonium nitrate. The vertical white "scars" are the vertical migration signatures of the ionic ammonium nitrate.

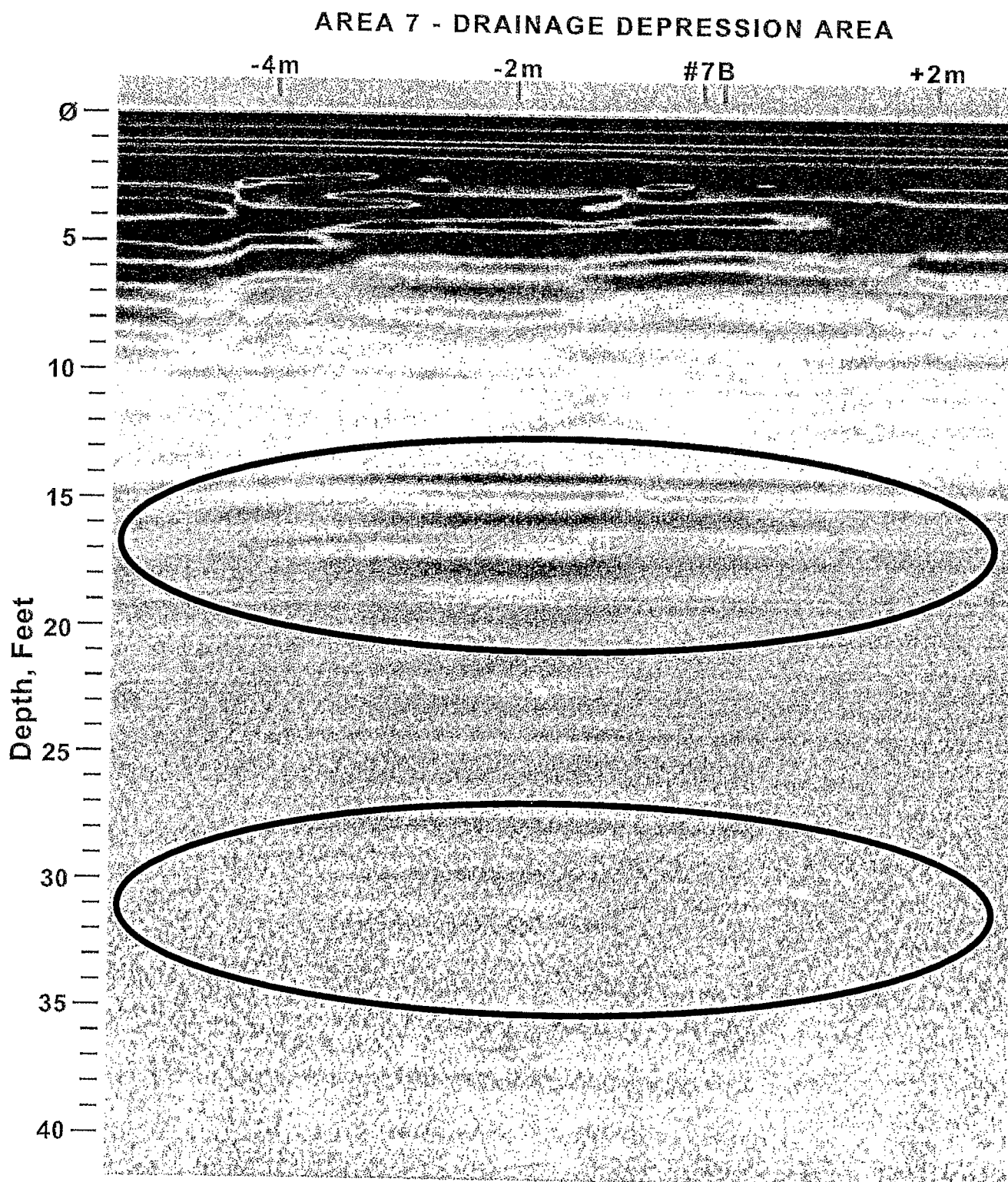


Figure 8. NITROGLYCERINE MAP/TAIWAN:
DNAPL signature of nitroglycerine
stratified in distinct vertical zones.

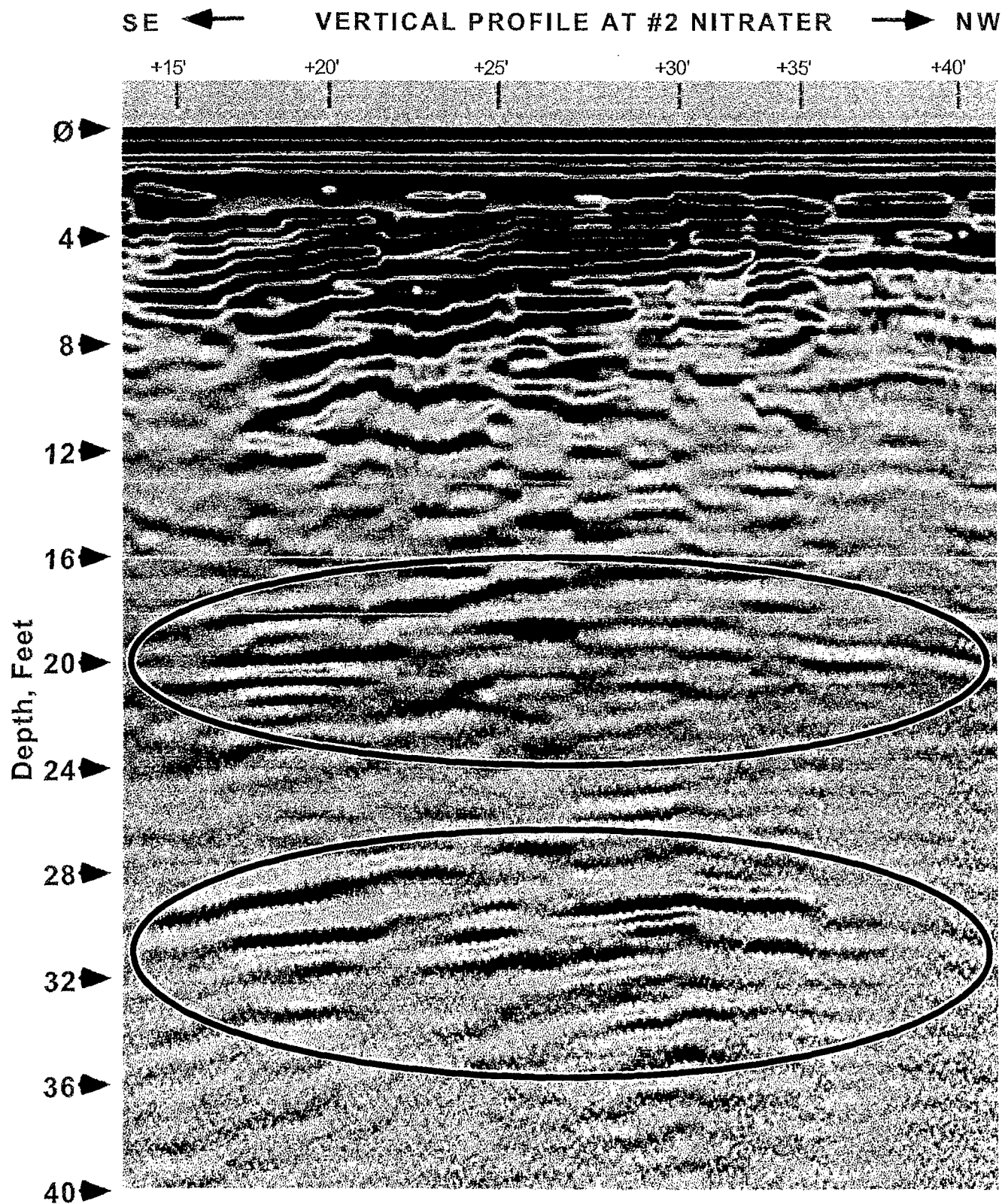


Figure 9. NITROGLYCERINE MAP/CANADA:
DNAPL signature of nitroglycerine
stratified in distinct vertical zones.

4. CONCLUSIONS:

Direct images have been made of low-level chemical contamination in the ground, including benzene, trichloroethylene (TCE), and explosives such as the nitroglycerine (NG). The detection capability is in the range of low parts-per-million (ppm) to upper parts-per-billion (ppb). The images were made with a modified, high performance ground-penetrating radar (GPR) system that was custom-designed to carry out these tasks. Each chemical/explosive has been found to have a unique radio frequency (RF) signature produced by the discrete energy bands of its molecule. This discovery has led to the creation of a new technology, electromagnetic radiography (EMR). Whereas GPR depends on the detection of subtle changes in the physical properties of the host material (soil) produced by the presence of a chemical contaminant, EMR is designed to detect the unique RF signature that is being generated by the chemical/explosive itself.

With the modified, high performance GPR/EMR technology, distinctions can be made between dense, non-aqueous phase liquids (DNAPLs) versus light, non-aqueous phase liquids (LNAPLs). The dissolved phase can be distinguished from the liquid phase. Chemicals and explosives can be broadly categorized as being ionic or non-ionic. In addition to being more specific in classifying chemicals and explosives, GPR/EMR technology is much more sensitive and has much higher spatial resolution than any other geophysical method, such as terrain conductivity (EM) or resistivity measurements. GPR/EMR is also immune to false responses produced by the lithology of the site.

During the course of the contract, the fundamental importance of naturally-occurring infiltration zones came to be understood. It was well known that dense, non-aqueous phase liquids (DNAPLs) tend to form vertical migration columns, or "sinkers." What was not previously understood is the tendency of DNAPLs, in response to the hydrology of the site, to migrate laterally above a confining layer or semi-confining layer until reaching an infiltration zone. These infiltration zones have lower density and higher permeability than the surrounding soils and provide a pathway for vertical migration down to the underlying aquifer. GPR/EMR technology is well suited for locating these contaminated infiltration zones and pin-pointing the optimum location for the placement of recovery well within these features.

The GPR/EMR technology is capable of providing high "production rates" by providing 100 percent inspection of 4 to 5 acres per day at depths up to 50 feet or more, resulting in the volumetric inspection of some 350,000 cubic yards of earth per day. The upper limit is the roughness of the terrain and the speed at which the equipment can cover the site. Because exploratory borings (drilling) can provide only a minuscule sample of subsurface conditions, it is almost a certainty that small, critical features such as a fault or an infiltration zone will be missed. By virtue of performing 100 percent volumetric site inspection at a cost per acre that is less than a single boring/drilling, GPR/EMR technology provides complete assurance that no critical feature will be missed and that the resulting level of understanding of site conditions will be vastly superior to the limited information that can be obtained from conventional borings.

Mission Research Corporation (MRC) and Detection Sciences Inc. (DSI) evaluated the feasibility of GPR/EMR technology as a non-intrusive technique for the detection of chemicals/explosives in the ground under the Phase I of this program. Our findings/conclusions have been much more favorable than we ever expected at the beginning of the program. GPR/EMR technology proved itself as an outstanding method for the detection of chemicals/explosives in the ground. Moreover, through our analysis and previous data evaluation, it has been realized that the GPR/EMR technology has the great potential of being able to **positively identify** explosives/chemicals underground.

5. RECOMMENDATIONS:

Although the EMR technology is sufficiently advanced to have compiled a significant record of accomplishments and capabilities, much work needs to be done to continue to make advances in this technology. The key areas for further development are:

- ♦ **Penetration.** Despite being able to penetrate nearly 50 feet under ordinary circumstances, including average clay conditions, there arise certain situations where penetration of the present EMR equipment is inadequate. For example, there may be free product on top of bedrock that may be 70, 80 or 100 feet deep, or more, beneath a clay layer. We would be able to identify vertical migration, or piping taking place in the infiltration zones in the upper soils, but be powerless to observe what is happening on top of the bedrock itself. In Florida, where the limestone, particularly pinnacle limestone, consists of ancient coral or sea bottom, the limestone has high electrical conductivity (low resistivity) that renders it relatively opaque to EMR. Standing water, such as borrow pits, can become mineral laden with alkali, including phosphates, that make it difficult to see deep in the ground beneath the water. Although we have achieved 18 feet of penetration in brackish water (about 1/3 the salinity of sea water), this may not be sufficient to observe the horizontal migration of DNAPLs lying beneath brackish marsh lands bordering the ocean.
- ♦ **Sensitivity.** We have numerous data points showing contamination levels in the low parts per million (ppm) to upper parts per billion (ppb). None the less, it would be invaluable to have the ability to see down to regulatory levels, such as 70 µg/kg Methyl Tertiary Butyl Ether (MTBE) or less. Not only would this let us find low level contaminants, we could also determine that the soil and water is "clean," or uncontaminated, down to the regulatory levels.
- ♦ **Physics of EMR.** We find that the physics related to observing chemicals in the ground is poorly understood. Specifically, we need better understanding at a very fundamental level, such as precisely what happens when radio frequency (RF) radiation interacts with solid matter. We sometimes observe phenomenon that we are unable to explain. We suspect that we are inducing certain types of quantum effects, but have no real evidence to support this assertion. We do know that various chemicals produce characteristic radar responses that differ from other chemicals. We have made numerous empirical observations and know that these EMR-induced phenomena are predictable, repeatable, and can be used to **positively identify specific chemicals** in the ground. For example, when soil tests show that we are observing TCE in the ground, we can use this information to "calibrate" the radar and produce a "TCE Map" with a high degree of certainty, even in the presence of other chemicals. But we do not know or understand exactly why TCE acts in the specific way that it does, or why it should produce the characteristic radar signature that we consistently observe.

The first two areas, penetration and sensitivity, are straight forward in the sense that increasing the transmitted power, decreasing the internal noise and improving the internal efficiency (duty cycle) of the radar equipment all work toward better penetration and sensitivity. More specifically, the improvements are in relation to the square root of the power increase, the noise reduction, or achieving a higher duty cycle. Together, each area results in gaining a certain number of dB. Ultimately, the earth can be characterized as losing a certain number of dB per foot of penetration (such as 0.5 dB per foot). Likewise, the radar can be characterized as having a certain number of dB — defined as the ratio of peak power to RMS noise. Therefore, the certain number of dB available; i.e., the dB budget as it were, determines the penetration depth and the sensitivity of the EMR equipment.

The physics is another matter. It is anticipated that a number of experiments and measurements will make it possible to "tease out" the answers to what is otherwise a perplexing set of empirical observations that we do not currently understand. A successful program featuring such well-thought experiments and measurements will make it possible to develop the capability and hence **positively identify explosives and other chemicals in the ground using EMR.**

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Environmental Restoration
AFDTC/EMR
207 N.2nd St., Bldg. 216
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Dr. Jimmy Cornette/Bruce Nielsen 2
Air Force Research Laboratory (AFRL)
Air Base and Environmental Technology Div.
AFRL/MLQE
139 Barnes Dr., Suite 2
Mail Stop 37
Tyndall AFB, Fl 32403-5323

Dr. Aka G. Finci 20
1720 Randolph Road, SE
Albuquerque, NM 87106-4245

Daniel Stanfill III 10
496 Heald Road
Carlisle, MA 01741